Introduction to superconducting quantum interference device (SQUID) and MEG system

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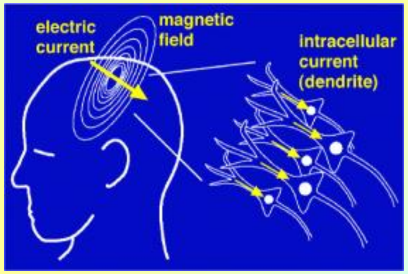
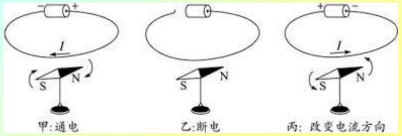
Outline

What is MEG?

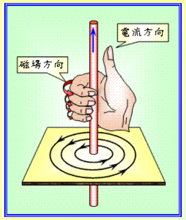
Magnetoencephalography (MEG) is an imaging technique used to measure the magnetic fields produced by electrical activity in the brain.



Current and Magnetic field

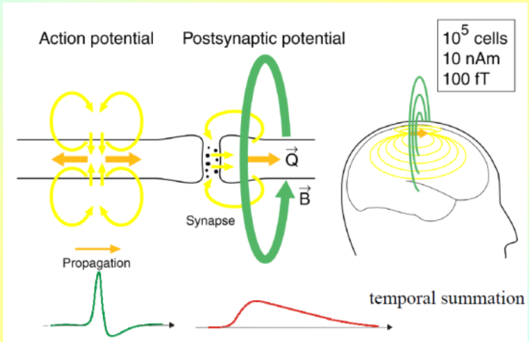


Electric current always generates a magnetic field!



Hans Christian Ø rsted (1777-1851) :Danish physicist and ch emist

Origin of Magnetic Field in The Brain



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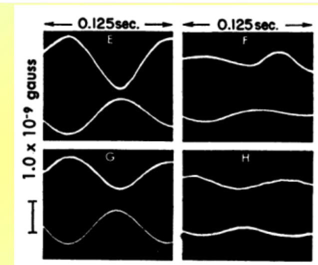
The first paper of MEG measurement:

Science vol. 161 pp. 784 (1968) by David Cohen

Magnetoencephalography: Evidence of Magnetic Fields Produced by Alpha-Rhythm Currents

Abstract. *Weak alternating magnetic fields outside the human scalp, produced by alpha-rhythm currents, are demonstrated. Subject and magnetic detector were housed in a multilayer magnetically shielded chamber. Background magnetic noise was reduced by signal-averaging. The fields near the scalp are about 1 × 10^{-9} gauss (peak to peak). A course distribution shows left-right symmetry for the particular averaging technique used here.*



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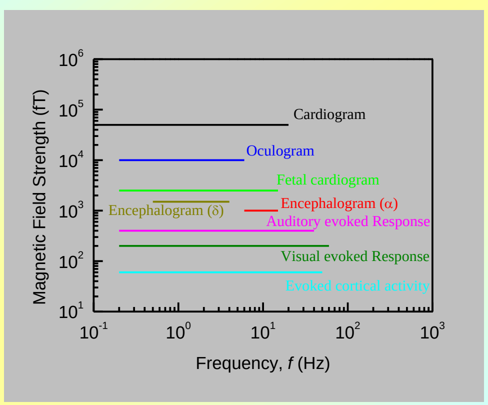
Strength of Representative Biomagnetic Fields



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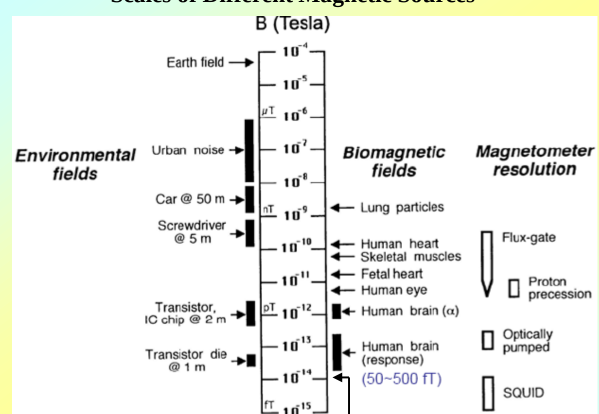
Scales of Different Magnetic Sources



The noise sensitivity of MEG system (10~100 fT)

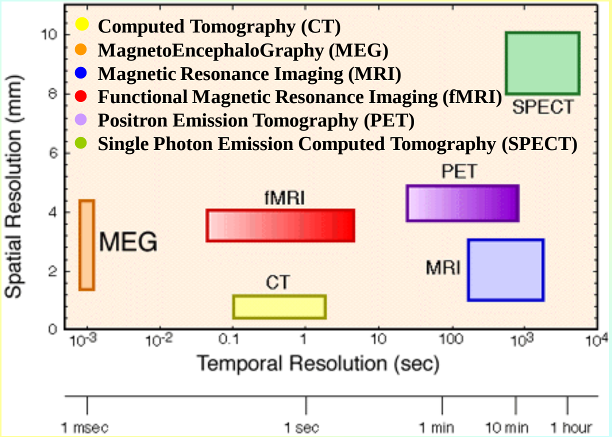
Some features of MEG

1. MEG is completely noninvasive and non-hazardous.
2. The data can be collected in the natural seated position allowing more life-like cognitive experiments than fMRI.
3. The measurement environment is completely silent, which facilitates especially auditory studies.
4. MEG has an extremely high temporal resolution (milliseconds) and also provides a good spatial resolution.
5. Signals can be recorded over the whole cortex.
6. There is no need to paste electrodes on the scalp as with EEG.

Modern Brain Imaging Techniques

Techniques	Spatial Resolution	Temporal Resolution
fMRI (functional Magnetic Resonance Imaging)	millimeter	seconds
PET (Positron Emission Tomography)	millimeter	seconds
MEG (Magneto-encephalography)	**millimeter**	**milliseconds**
EEG (Electro-encephalogram)	centimeter	milliseconds

MEG vs. Other Techniques



Some novel researches performed with MEG

◆Clinical diagnosis:

1. Focal epilepsy (癲癇症)
2. Alzheimer‘s disease (阿茲海默症)
3. Schizophrenia (精神分裂症)
4. Multiple sclerosis (多發性神經硬化症)
5. Chronic alcoholism (慢性酒精中毒)

⋮ etc.

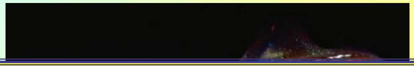
◆Cognitive behavior study:

1. Learning
2. Memory
3. Vision
4. Audition
5. Language processing

⋮ etc.

Outline

1. What is the MEG?
2. What is the SQUID?
3. Introduction to dc SQUID magnetometer and gradiometer
4. Introduction to Magnetoencephalography (MEG) system
5. Summary

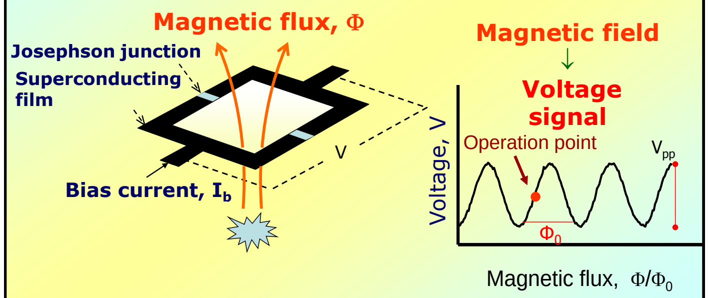


What is the squid?

From Cambridge Dictionaries online:
squid
noun [C or U]
a sea animal with a long body and ten arms situated around the mouth, or this animal eaten as food

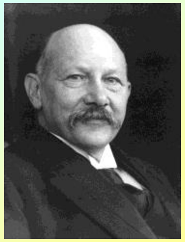
I am squid !!!

- Superconducting QUantum Interference Devices (SQUIDs)

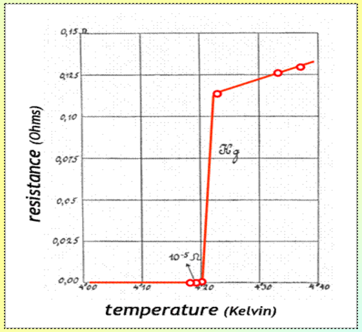


The SQUID is a flux-to-voltage converter.

Superconductivity

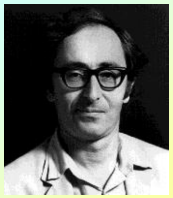


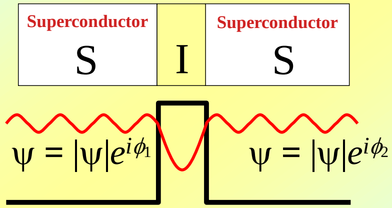
Heike Kamerlingh Onnes was the pioneer to liquefy helium. In 1911, he found the superconductivity for certain materials. Because of the great discovery, he won the Nobel Prize in Physics in 1913.



Zero electrical resistance !

Josephson Effect



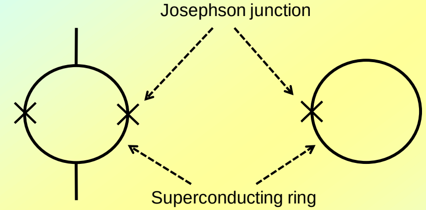


In 1962, the 22-year-old British student Brian David Josephson predicted two effects which could experimentally verified shortly afterwards. The modern Josephson voltage standard is based on one of these effects. He became a Nobel Prize laureate in Physics in 1973.

$$\begin{cases} I = I_C \sin\phi, \ \phi = \phi_1 - \phi_2 \\ \dfrac{d\phi}{dt} = \dfrac{-2eV}{\hbar} \end{cases}$$

B.D. Josephson, "Possible new effects in superconductive tunnelling", Phys. Lett. **1** (1962) 251-253.

Superconducting QUantum Interference Devices (SQUIDs)



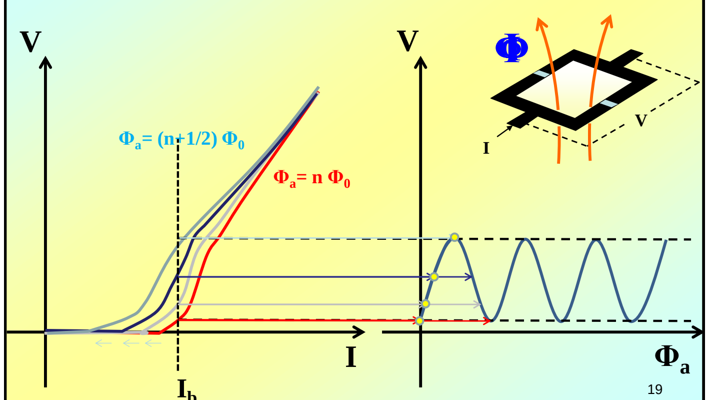
dc SQUID

R. C. Jaklevic, J. Lambe, A. H. Silver, and J. E. Mercereau, "Quantum interference effects in Josephson tunneling," *Phys. Rev. Lett.*, vol. **12**, pp. 159–160, Feb. 1964.

rf SQUID

A. H. Silver and J. E. Zimmerman, "Quantum transitions and loss in multiply connected superconductors," *Phys. Rev. Lett.*, vol. **15**, pp. 888–891, Dec. 1965.

I-V & V- Φ Characteristics



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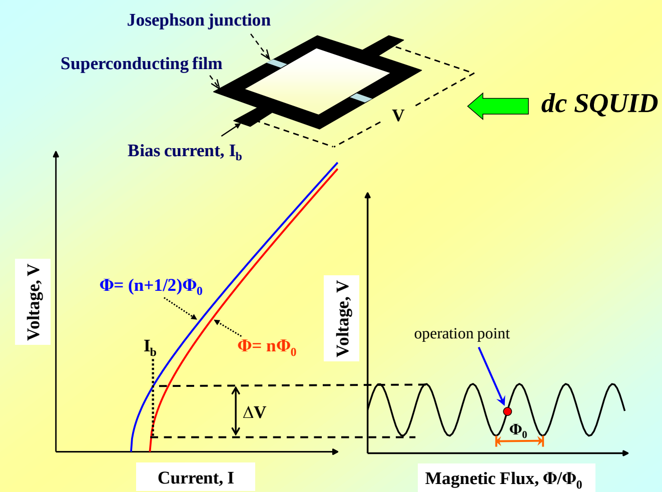
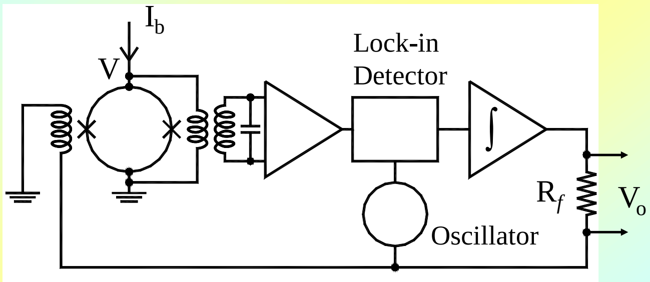
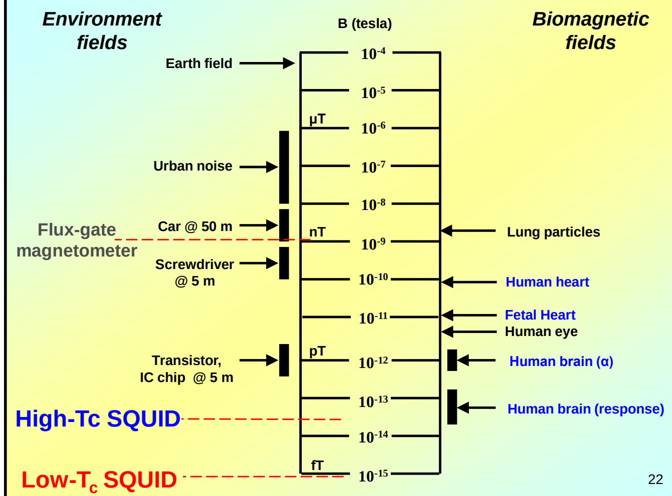


Schematic of dc SQUID Electronics



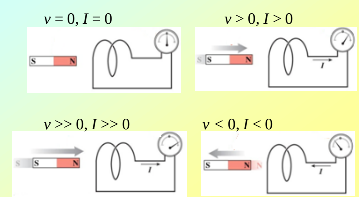


Outline

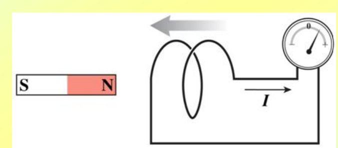
1. What is the SQUID?
2. What is the SQUID?
3. Introduction to dc SQUID magnetometer and gradiometer
4. SQUID applications
5. Summary

Induced Currents　感應電流

4 results from Faraday / Henry (1831)　法拉第 / 亨利 (1831) 的四個結果



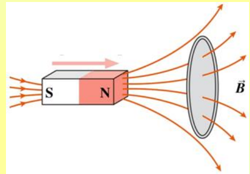
1. Current induced in coil by moving magnet bar.
   移動磁鐵會在線圈引發(感應)電流。



2. Moving the coil instead of the magnet gives the same result.
   不移磁鐵，改移線圈有同樣結果。

Magnetic flux 磁通量與感應電動勢

Magnetic flux:
磁通量： $\Phi_B = \int \mathbf{B} \cdot d\mathbf{A}$



For a uniform **B** on a flat surface:
均勻 **B** 在平面上：

$$\Phi_B = \mathbf{B} \cdot \mathbf{A} = BA\cos\theta$$

Move magnet right → more lines thru loop
磁鐵右移 → 多些場線穿過迴路：

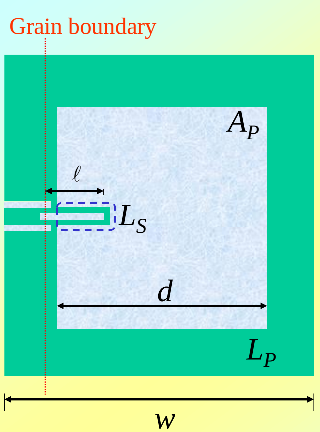
Faraday's law of induction 法拉第的感應定律:
The induced emf in a circuit is proportional to the rate of change of magnetic flux through any surface bounded by that circuit.
一個線路的感應電動勢，與穿透任何由這線路圍住的表面的磁通量時間變化率成正比。

$$\oint_c \vec{E} \cdot d\vec{l} = \varepsilon = -\frac{d\Phi_B}{dt} = -\frac{d}{dt}\int_s \mathbf{B} \cdot d\mathbf{A}$$

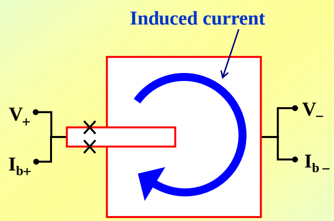
The sensitivity relation : $S_B^{1/2}(f) = \dfrac{S_\Phi^{1/2}(f)}{A_{eff}}$

Where $S_\Phi^{1/2}(f)$ and A_{eff} are the flux noise and the effect area.

To design a sensitive SQUID magnetometer, one should increase the effective area A_{eff} or reduce the flux noise $S_\Phi^{1/2}$ to improve the field sensitivity $S_B^{1/2}$.



Directly-coupled SQUID



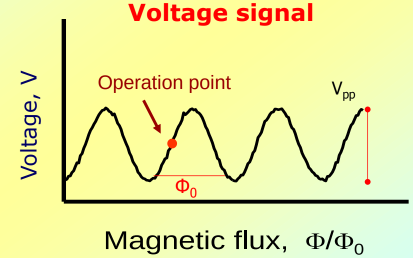
$$A_{eff} = A_{SQ} + \alpha L_{SQ} \frac{A_P}{L_P}$$

$$S_\Phi^{1/2} = \frac{S_V^{1/2}}{V_\Phi} = \frac{S_V^{1/2}}{\left(\dfrac{\partial V}{\partial \Phi}\right)}$$

Voltage noise ≈ $(16k_BTR_0)^{1/2}$ (white)

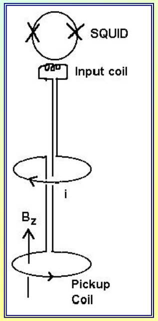
Flux-to-voltage transfer function

Magnetic field
↓
Voltage signal



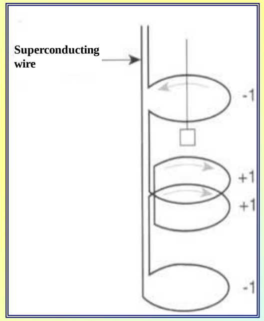
Gradiometer

First-Order Gradiometer



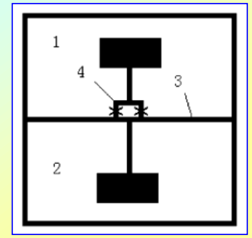
Insensitive to B_{z0}

Second-Order Gradiometer



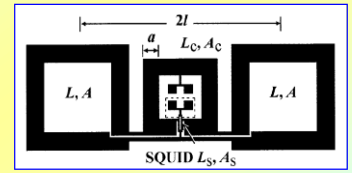
Insensitive to B_{z0} and $\partial B_z/\partial Z$

High-T_c Planar Gradiometer



First-Order Gradiometer

Physica C **411** (2004) 53-58

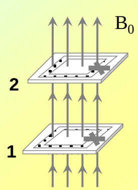


Second-Order Gradiometer

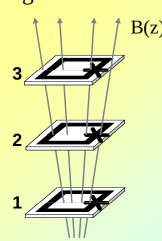
Appl. Phys. Lett. **84**, No. 4, 568 (2004)

Electronic gradiometer **based on high-T_C SQUID magnetometers:**
Superconducting loops on separate chips form the gradiometer through electronic compensations

1^{st}-order electronic gradiometer

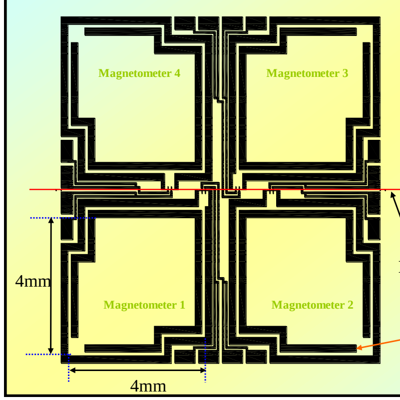


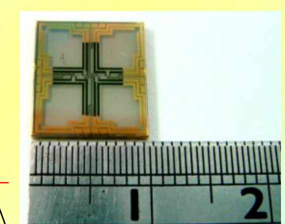
2^{nd}-order electronic gradiometer



Y. Tavrin, Y. Zhang, Y. Mück, A.I. Braginski and C. Heiden, Appl. Phys. Lett., **62, 1824-1826, (1993).*

Schematic diagram of integrated four magnetometers





Bicrystal line

Modulation coil

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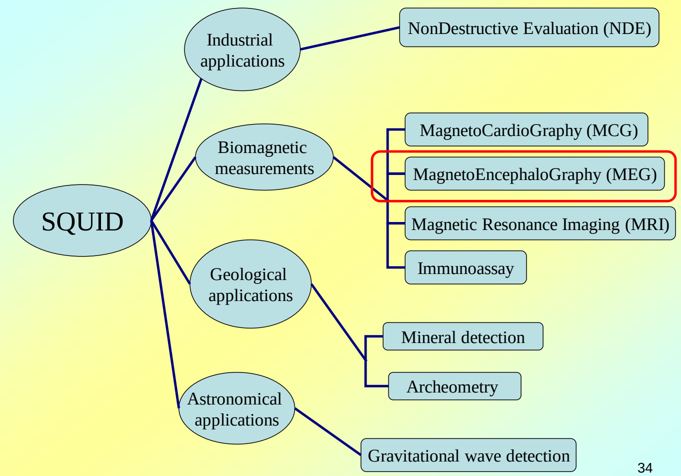

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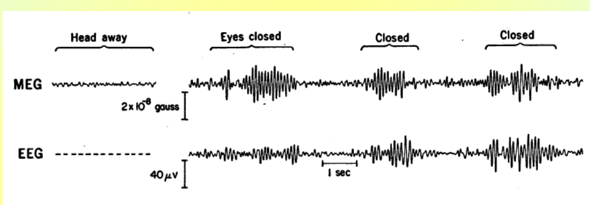
The first paper of MEG measured by the SQUID :

***Science* vol. 175 pp. 664 (1972)** by David Cohen

Magnetoencephalography: Detection of the Brain's Electrical Activity with a Superconducting Magnetometer

Abstract. *Measurements of the brain's magnetic field, called magnetoencephalograms (MEG's), have been taken with a superconducting magnetometer in a heavily shielded room. This magnetometer has been adjusted to a much higher*



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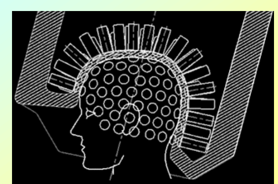
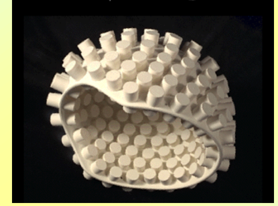
Structure of magnetoencephalographic sensing system

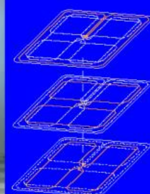
CTF Systems Inc.





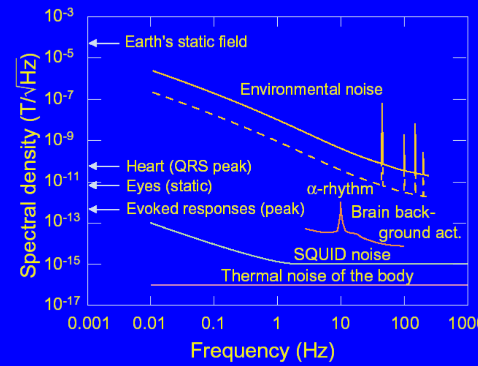
Example (Vectorview)

- 306 channels
- Triple sensor elements



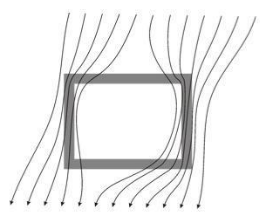
Elekta Neuromag

Signal and noise sources



Magnetically Shielded Room

- A passive shield against environmental magnetic noise
- Concentric shells of mu-metal and aluminium



External magnetic field 'bends' around the magnetically-shielded room

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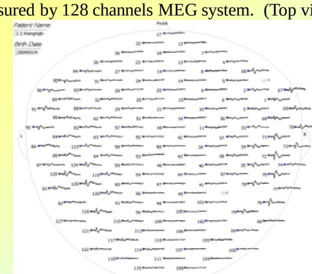
Magnetically shielded rooms

- Mu-metal/Aluminium structure
- Shielding enhanced by active compensation
- Typical performance:
  0.1 Hz –40 dB
  1.0 Hz –60 dB
  10 Hz –80 dB

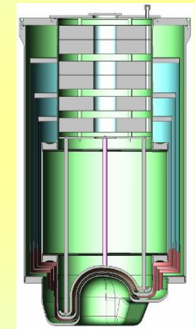
The configuration of SQUID sensors

The magnetic signals generated from human brain measured by 128 channels MEG system. (Top view)



Helmet-type dewar (頭盔狀杜瓦瓶)

MEG 系統杜瓦瓶外觀圖



MEG 系統杜瓦瓶剖面圖

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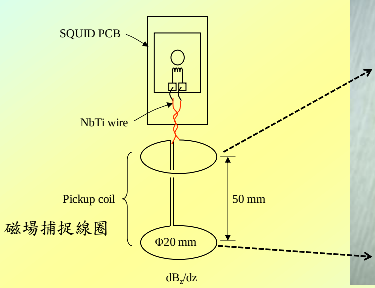
The first-order Gradiometer used in the 128-channel MEG system

MEG系統使用一階梯度計量測磁場訊號

First-order gradiometer



Pickup coil is made of **NbTi** wire wound on a non-magnetic fiber glass reinforced plastic.

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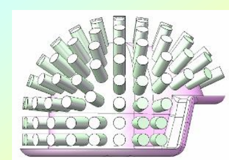
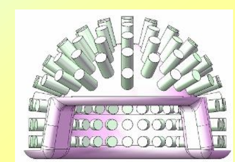
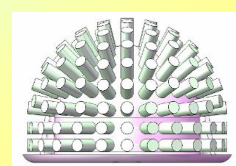
SQUID Sensor layout (感測器的空間分布)



Side側視圖



Front前視圖



Back後視圖

實際照片

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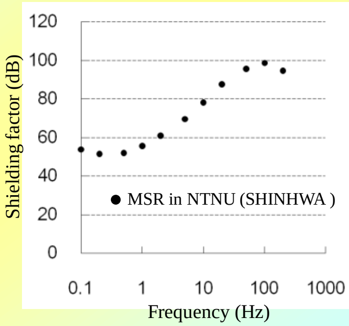
Magnetically Shielded Room (MSR) in NTNU

MSR-SH100
(SHINHWA ENGINEERING CO., LTD.)



Inner dimension : 2.8 m (L) x 2.2 m (W) x 2.4 m (H)
Outer dimension : 3.2 m (L) x 2.6 m (W) x 2.9 m (H)

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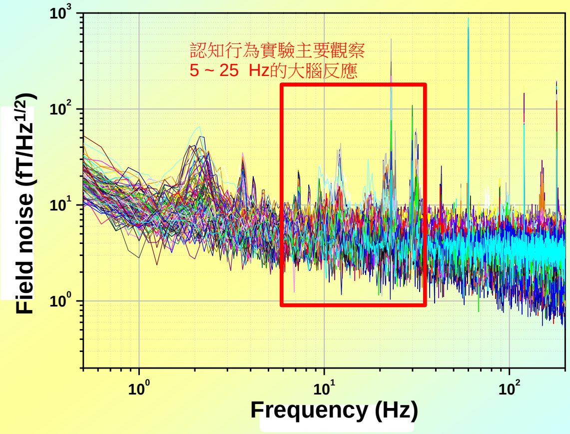
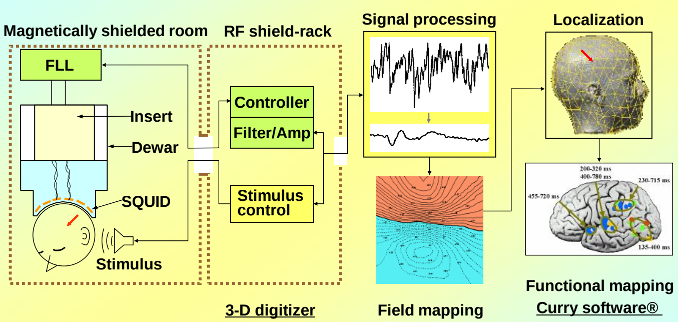
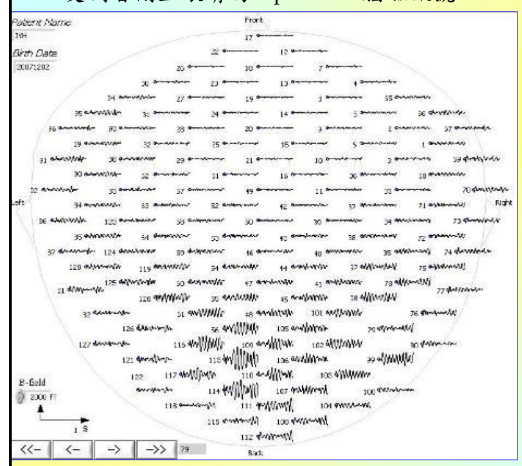
Noise spectra



Flowchart of MEG measurement



受測者閉上眼睛的Alpha wave腦磁訊號

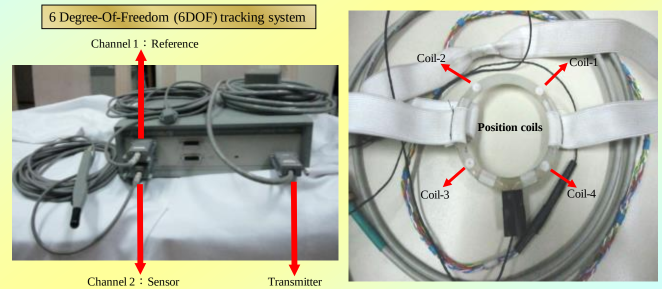


1.受測者閉上眼睛時會使Alpha wave增強而影響我們所要觀察的腦磁訊號。

2.除非作睡眠或閉眼的實驗，否則實驗時不可閉眼或睡覺。

How can we know where the subject's head is within the MEG helmet?

In order to determine the subject's head within the MEG helmet, we perform the "**localization**" before MEG measurement.



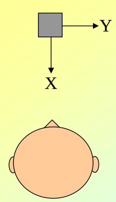
Polhemus Fastrak定位系統

Transmitter (電磁波發射器)

筆型電磁波接收感測器

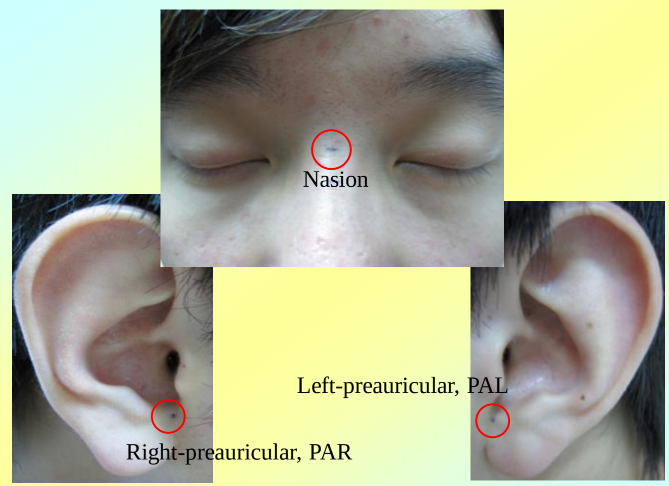
Reference

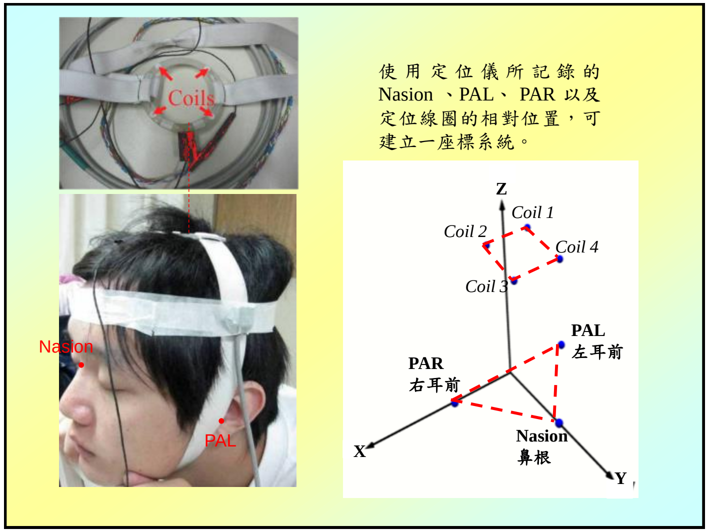
Transmitter

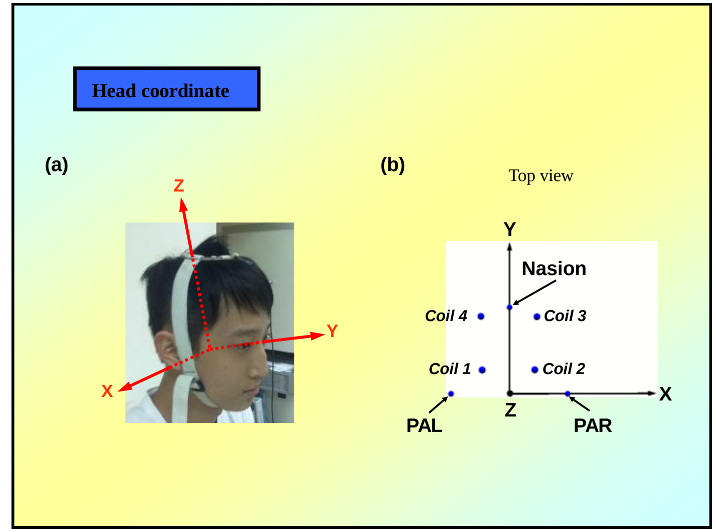


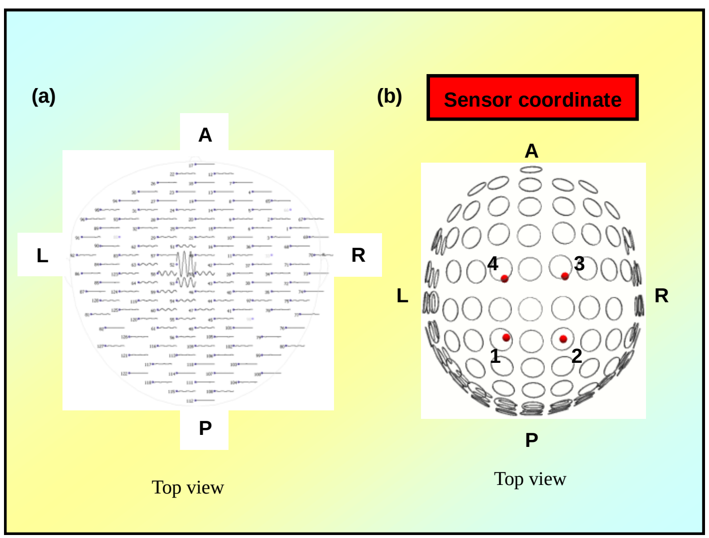
Subject

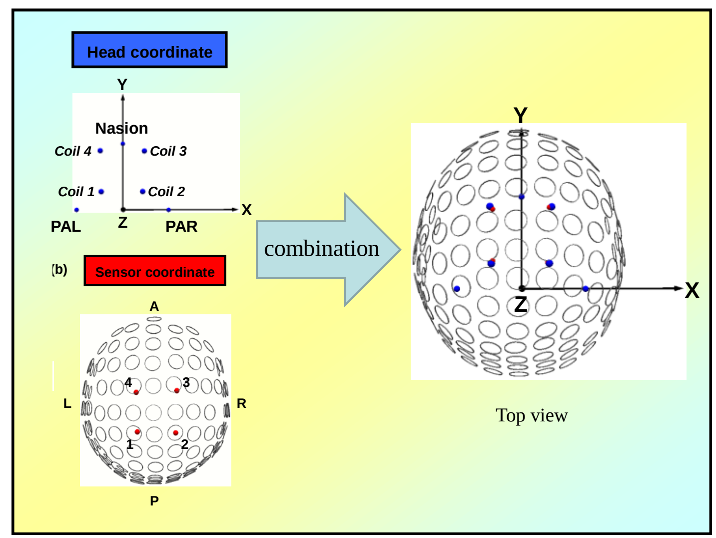
Transmitter 擺放位置置於受測者前方，座標方位如圖表示。




Coils
Nasion
PAL
使用定位儀所記錄的Nasion、PAL、PAR以及定位線圈的相對位置，可建立一座標系統。
Z
Coil 1
Coil 2
Coil 4
Coil 3
PAL
左耳前
PAR
右耳前
Nasion
鼻根
X
Y

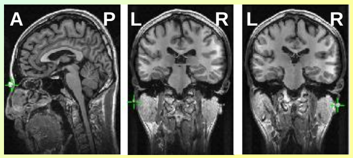

Head coordinate
(a)
(b)
Top view
Z
Y
X
Y
Nasion
Coil 4
Coil 3
Coil 1
Coil 2
X
Z
PAL
PAR


(a)
(b)
Sensor coordinate
A
L
R
P
Top view
A
L
R
P
4
3
1
2
Top view


Head coordinate
Y
Nasion
Coil 4
Coil 3
Coil 1
Coil 2
X
PAL
Z
PAR
(b)
Sensor coordinate
A
L
R
P
combination
Y
X
Z
Top view

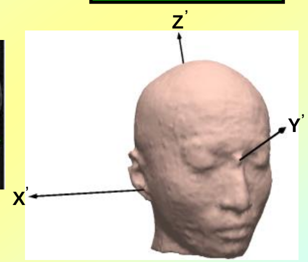
Virtual brain construction

(a)

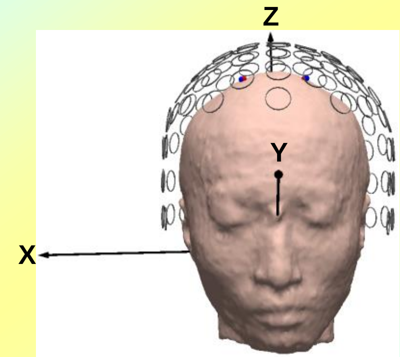


Magnetic Resonance Images

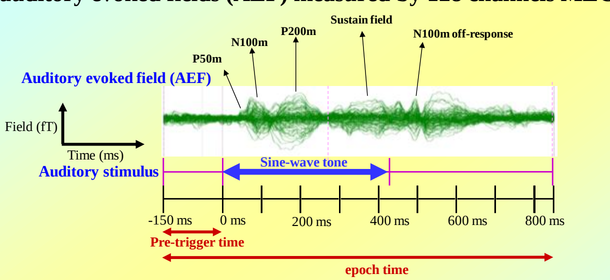
(b)



The relative position of a subject's brain in the 128 channel SQUID helmet



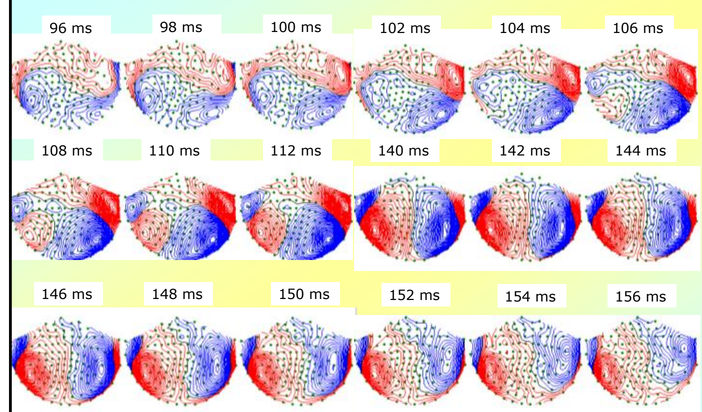
The auditory evoked fields (AEF) measured by 128 channels MEG



Stimulus parameters:

Frequency: 500 Hz
Duration: 425 ms
Sound input: **Left ear**

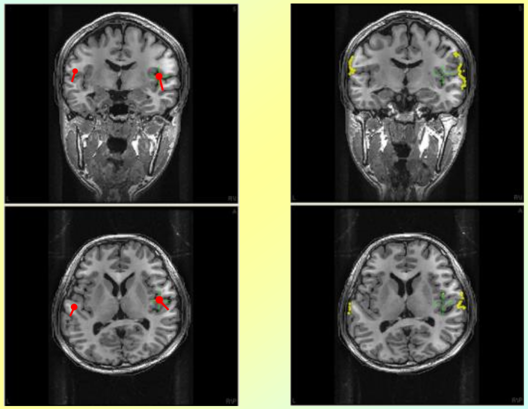
AEF recording:
Sampling rate: 1000 Hz
Pre-trigger time: 150 ms
Epoch time: 1 s
Average: 100 epochs
Characteristic peaks of the AEFs: P50m, N100m, P200m, and N100m off-response.



The temporal evolution of the AEF signals is shown by 2-D isofield contour map around the N100 peak.

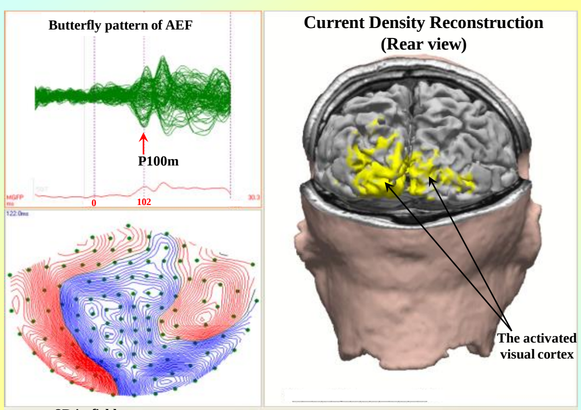
The activated area in the brain corresponding to the peak signal of N100m on-response

Equivalent Current Dipole calculation | **Current Density Reconstruction**



The visual evoked magnetic field measurement

The P100m signal of visual evoked magnetic field (VEF)



2D isofield contour map (Top view)

Outline

1. What is the SQUID?
2. Introduction to dc SQUID magnetometer and gradiometer
3. Introduction to Magnetoencephalography (MEG) system
4. Summary

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Summary

1. MEG is completely noninvasive and non-hazardous.
2. The data can be collected in the natural seated position allowing more life-like cognitive experiments than fMRI.
3. The measurement environment is completely silent, which facilitates especially auditory studies.
4. MEG has an extremely high temporal resolution (milliseconds) and also provides a good spatial resolution.
5. Signals can be recorded over the whole cortex.
6. There is no need to paste electrodes on the scalp as with EEG.

Thanks for your attention!